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Heating of the Polar Ionosphere

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Introduction: As technology advances, modern society and especially the military rely on space-based assets. Sensitive systems include communications, surveillance, and navigation. Consequently, understanding and predicting "space weather"—the state of the environment in near-Earth regions—has become increasingly critical.

Recently, geomagnetic storms have come to the public's attention through the popular press. For example, the great storms that occurred around Halloween in 2003 were widely reported in the news. Adverse effects resulting from the impact of geomagnetic storms include the loss of satellite services because of electronic disruption and outages in the electric power grids from surges. In this article, we discuss research on another consequence of geomagnetic activity, namely, the large amount of energy deposited in the polar ionosphere. During geomagnetic storms, the heated ionosphere and neutral atmosphere expand, increasing density at high altitudes so that satellites experience enhanced drag. As a direct result, orbits are altered, communications to other satellites or to the ground can be disrupted, and the spacecraft may require a "boost" to continue its mission.

Background: The source of the energy responsible for heating the ionosphere and atmosphere is the Sun. Normally, solar radiation is the primary contributor. However, during solar disturbances, the solar wind plays an increasingly important role. The solar wind is a plasma that continually streams radially away from the Sun. The solar wind also carries a magnetic field called the Interplanetary Magnetic Field (IMF). During solar storms, the solar wind is greatly enhanced, with the density and IMF strength many times the nominal values. These solar storm events can last more than a day and are often associated with the occurrence of a coronal mass ejection (CME) on the Sun. This was the case for the 2003 Halloween storms. When the direction of the disturbed IMF as it reaches the Earth is opposite to the direction of the Earth's magnetic field, a geomagnetic storm occurs, and the solar wind energy flowing into the magnetosphere and downward to the ionosphere is greatly enhanced. In recent years, considerable effort at NRL and other research institutions has been devoted to studying and predicting these conditions and their effects.

Two main processes deposit solar wind energy in the polar ionosphere: resistive heating and energetic particle precipitation. Electric currents are driven by the solar wind-magnetosphere interaction. They flow along geomagnetic field lines into the ionosphere in the polar regions, where they flow across the magnetic field at altitudes around 100 km and then return to the magnetosphere. During geomagnetic storms, these currents can exceed 10 million amperes. In a manner similar to a wire heating from resistance to current, the ionosphere is heated. The total resistive heating rate can exceed 1 trillion watts during the peak of a geomagnetic storm.

The electromagnetic forces from the solar wind-magnetosphere interaction also accelerate plasma in the outer magnetospheric regions. A well-known consequence of energetic particle precipitation is the aurora. High-energy electrons and ions travel down the geomagnetic field and, as they encounter the dense atmosphere, excite the atoms and molecules that emit the light we see. During geomagnetic storms, the precipitating particles are greatly enhanced, and the power entering the ionosphere can be several 100 GW.

Model Description: Our research uses numerical simulation models to study polar capionosphere heating. The Lyon-Fedder-Mobarry (LFM) global magnetosphere model was developed at NRL in the early 1990s. It is a three-dimensional (3D) ideal magnetohydrodynamics representation of the Earth's magnetosphere, which is driven by solar wind data as input and is coupled to the ionosphere in the polar regions. The LFM model is also used at several universities and is the flagship magnetosphere model at the Center for Integrated Space Weather Modelling, (CISM), a National Science Foundation Science and Technology Center headquartered at Boston University.

Two types of studies are involved in this research. In one, we specify the solar wind and other conditions, such as the solar radiation output or the season of the year, to see how the polar cap heating responds. Secondly, we use measured conditions to simulate real events. Figure 5 is an example from the simulation of the effect of a shock front in the solar wind that hit Earth on 04 November 2003 during the Halloween geomagnetic storm period. The top row shows contours of the resistive and precipitation heating rates in the southern polar cap at 0651 UT. The polar plots are centered on the magnetic pole, and the circles

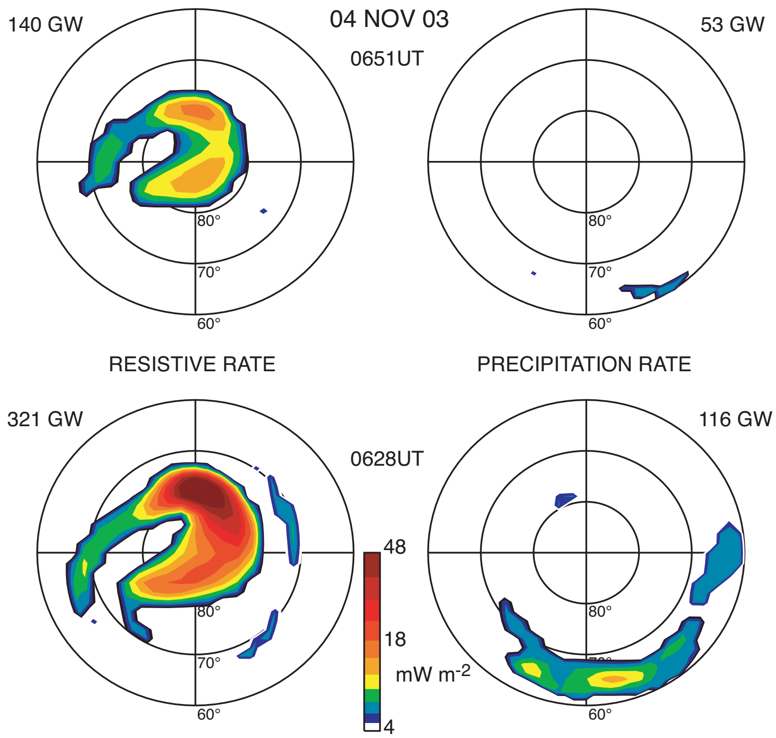

FIGURE 5
Polar plots of contours of resistive and precipitation heating for the southern hemisphere on 04 November 2003. The top row shows heating approximately 6 min before a solar wind shock wave arrives. The bottom row is taken about 6 min after arrival.

are drawn every 10 deg of latitude. The shock front arrived at about 6 min later. The bottom row of the plot gives the heating rates after another 6 min. We see that both rates have more than doubled.

The ionospheric results from the LFM simulation can be used as input to the NRL ionosphere model, SAMI3. This is a 3D simulation that resolves the ionosphere from the polar regions to the equator. SAMI3 can predict the "swelling" of the ionosphere from the heating and the resulting winds.

Summary: Geomagnetic storms can deposit sufficient energy in the polar ionospheres to cause the atmosphere to expand upward. The increased atmospheric density enhances atmospheric drag on low-altitude spacecraft and causes their orbits to decay. We are performing simulation studies to understand this and other processes to predict their impacts on space weather conditions and on space-based systems.

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